Beyond the baseline coronagraph science case: Could AFTA detect and characterize ExoEarths ?

This question should be addressed in our report

Consequences of answering “Yes”: risk failure to deliver on a promise
Consequences of answering “No” (or avoiding the question): missing an opportunity, having to wait for ~20yr

A constructive answer to this question should outline steps that need to be taken to enable future detections of ExoEarths with AFTA, under program constraints (cost, schedule, minimal impact on core WFIRST program)

The real answer is: “… quite possibly, but ...”
(1) It cannot be guaranteed → Cannot be part of a deliverable
(2) Requires more study to get better answer

However, looking at this challenge from a technical level teaches us that:
(1) Baseline vs. “enhanced instrument” has little (no ?) impact on cost
(2) “enhanced instrument” TRL similar to baseline TRL
(3) “enhanced instrument” option offers convincing gains to baseline science

Note: “enhanced instrument” = higher efficiency coronagraph with smaller IWA than baseline

How AFTA changes the rules of the game

Dedicated exoplanet imaging mission would face considerable challenges. Two separate stategies doomed to failure:

"We can image disks and Jupiters (+ spectroscopy) in ~15yrs for >$1B" → not compelling, not unique (ground-based observations), too focused, limited community support

"We'll try spectroscopy of Earths for ~$2B but we're not sure we'll succeed" (planet statistics, exozodi, technical challenges) → too risky for the cost

Challenge: Direct imaging of Earth like planets fundamentally requires D>~2m, so it cannot be cheap

The BEST path to direct imaging of Earth-like planets is with a program that can survive failure of imaging Earth-like planets → AFTA (or any other program where coronagraph is not the core instrument) is the way to go !

There is a compelling case for trying to image and characterize Earths with AFTA:
(1) It could work !
(2) It will teach us how to think about the next steps (future mission ?) - lab doesn't tell us the whole story
(3) It enhances the baseline science, and mitigates technical risks for the baseline science

TRL, cost, risk

TRL of components is high** **(except DM)**, **system TRL is low

Coronagraphs work in labs at the required contrast :
- coronagraphy at 1e-9 RAW contrast demonstrated at 2 l/D with full efficiency
- pointing control to sub-mas demonstrated in 3 separate labs with coronagraph (2 air, 1 vacuum)
- broadband WF control demonstrated at the 1e-9 contrast level

BUT:
- all demonstrations listed above have not all been integrated in a single testbed meeting requirements
- spectroscopy + coronagraphy + WFC not yet integrated
- systems work in labs with lots of attention, but not continuously / remotely / robustly for long period of time
- high precision WF control in space is new, DM longevity in space env. unproven, lots of "details" still need to be figured out (e.g. on-board computing power for WF control)

Telescope stability requirement for high contrast imaging has not been quantified for AFTA: how good can we do with a telescope that was not specifically designed for high contrast imaging ?
(We need to do this work very soon for AFTA)

The low TRL issues are somewhat decoupled from the coronagraph concept, but are closely linked to the coronagraph instrument architecture → "enhanced coronagraph" option not likely to increase cost, risk or schedule

“enhanced coronagraph” (=efficient) on a 2.4m aperture

SCIENTIFIC MOTIVATIONS:
(1) With a full efficiency* coronagraph, a 2.4m telescope could potentially directly image and acquire low resolution spectra of rocky planets in the habitable zones of nearby stars. (significant part of TPF-C goal) → Can this goal be reached ?
(2) Full efficiency coronagraph still works well at 4 l/D, and probably does work much better at 4 l/D than baseline coronagraph designed only for 4 l/D IWA

1l/D IWA, 100% efficiency on 2.4m would be superior to TPF-C FB1, that had 4 l/D on a 3.5m x 8m and few percent efficiency

(*) Full efficiency coronagraph: fully removes starlight while preserving the angular resolution and sensitivity of the telescope with inner working angle ~ 1 l/D

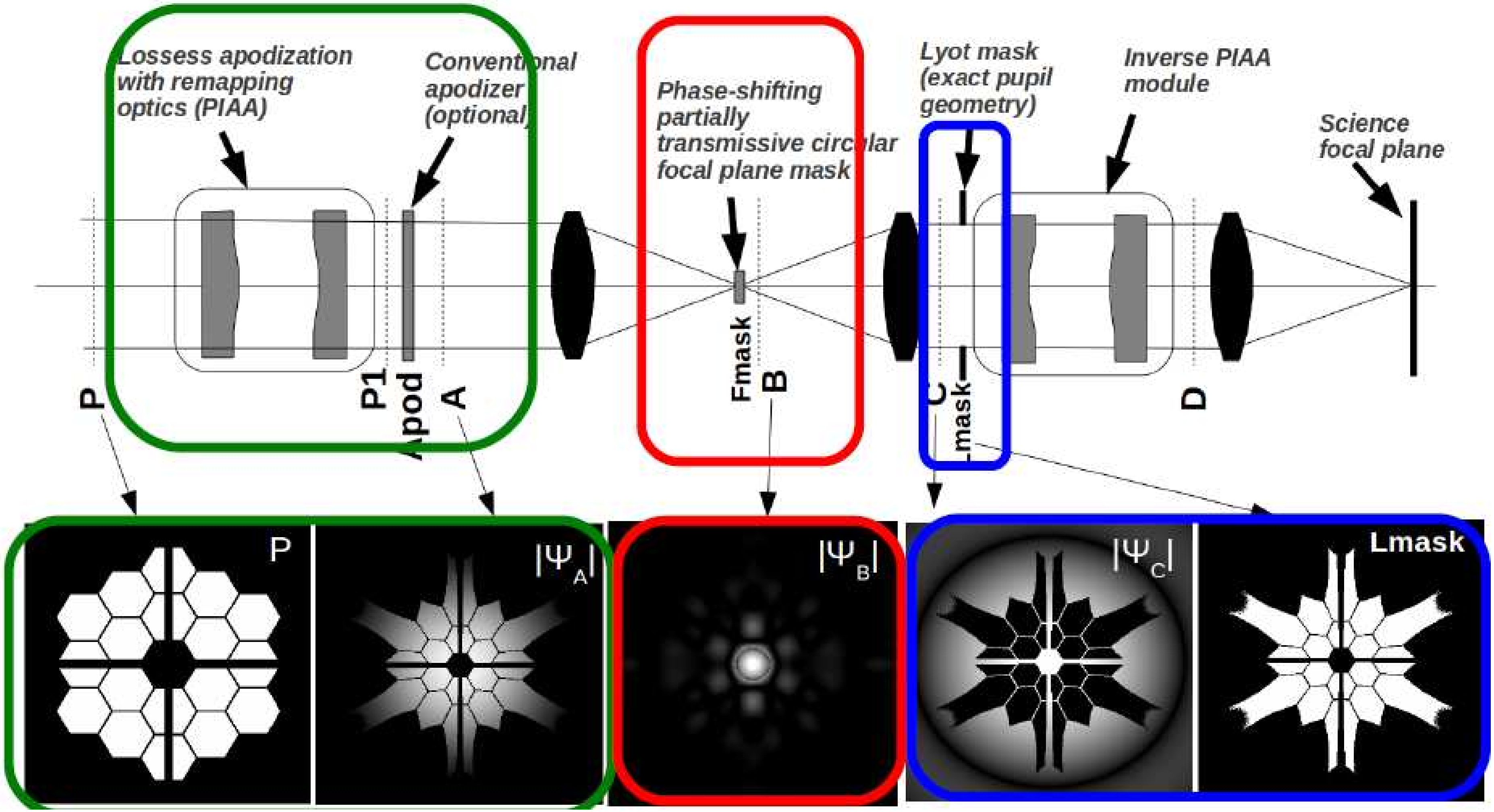
PIAACMC (described in this presentation) is one example of a coronagraph that approaches full efficiency – used in this presentation to illustrate scientific opportunities and also technical challenges associated with an efficient coronagraph option.
OTHER OPTIONS EXIST: Vortex (Mawet), apodization + phase mask (Carlotti)

How does PIAACMC work ?

Combines 3 techniques :

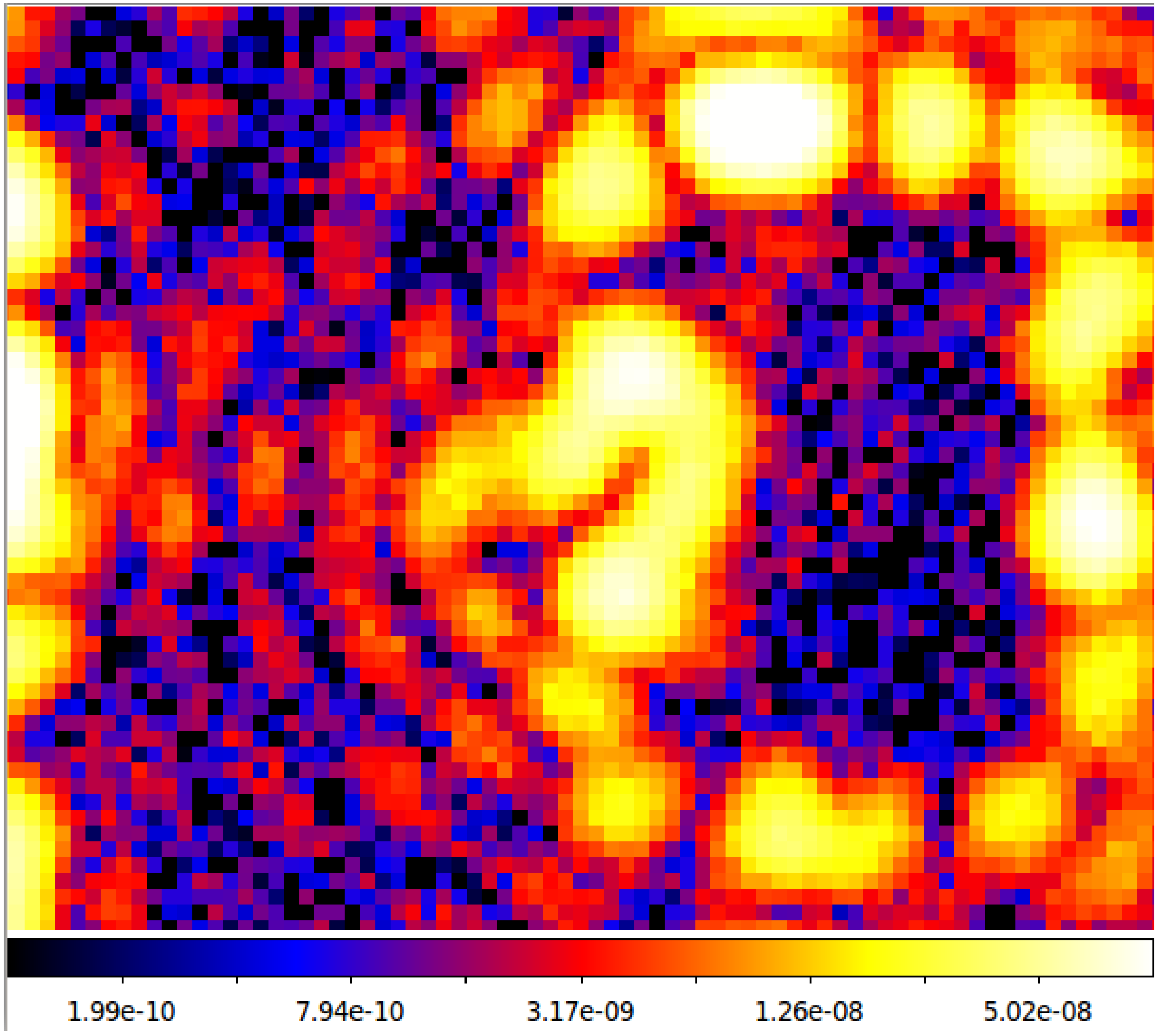
- **Lossless apodization with PIAA optics (beam shaping)**
- **Phase mask coronagraphy (focal plane mask is phase-shifting)**
- **Lyot coronagraphy (Pupil plane Lyot mask removes starlight)**

→ starlight rejection achieved by **destructive interference** between light that passes through the focal plane mask and light that passes outside the focal plane mask



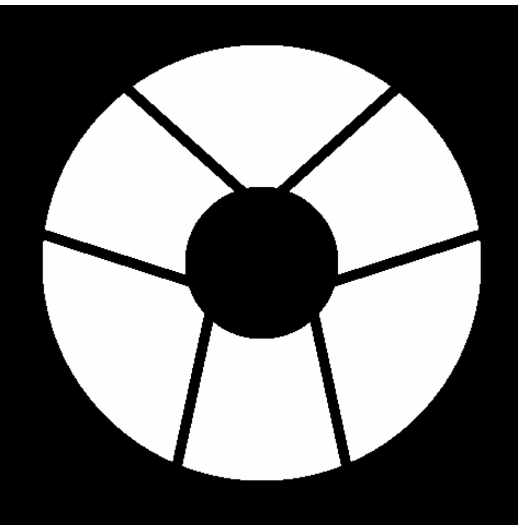
Recent PIAA results from HCIT

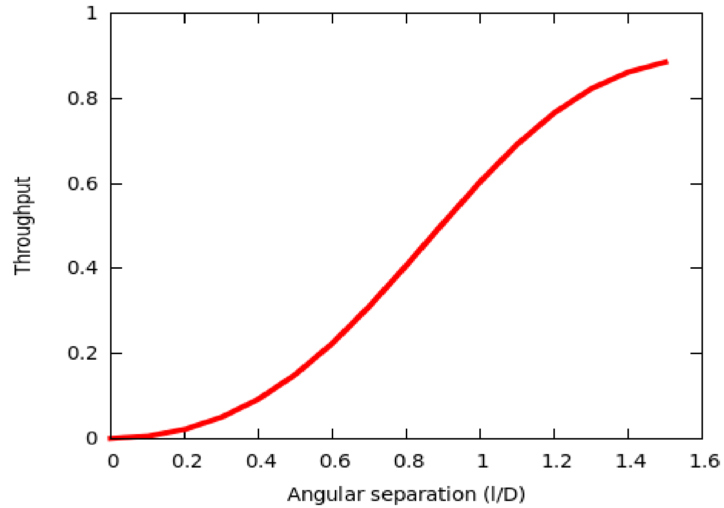
Average contrast between 2 and 4 l/D better than 1e-9 (IWA=1.76 l/D)
EFFICIENCY ~100% (no apodizer)

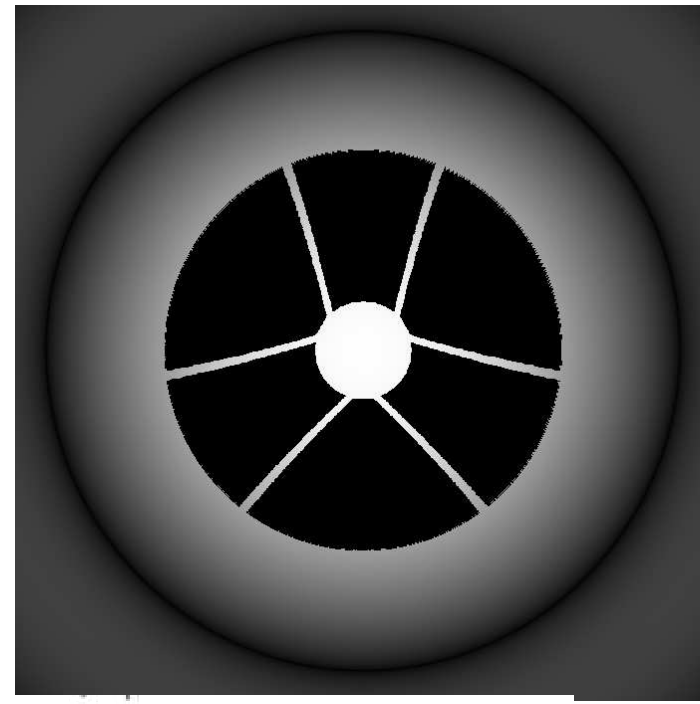


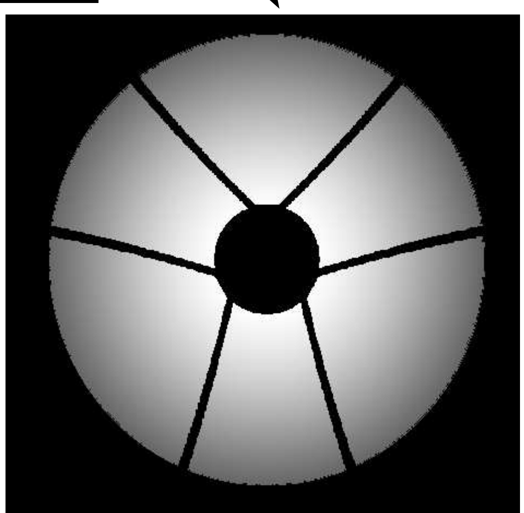
PIAACMC on AFTA pupil

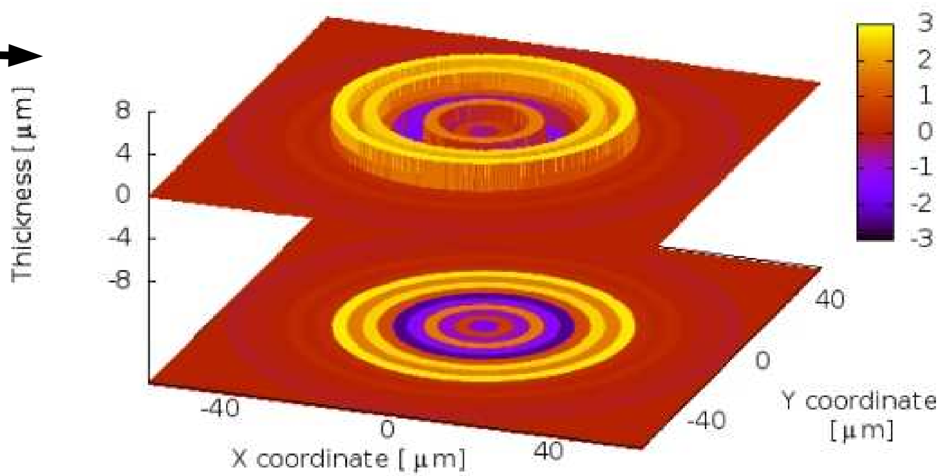
No loss from central obstruction and spiders
100 % efficiency, IWA can be designed to 0.65 l/D (but pushed to ~0.9 l/D to mitigate stellar angular size)





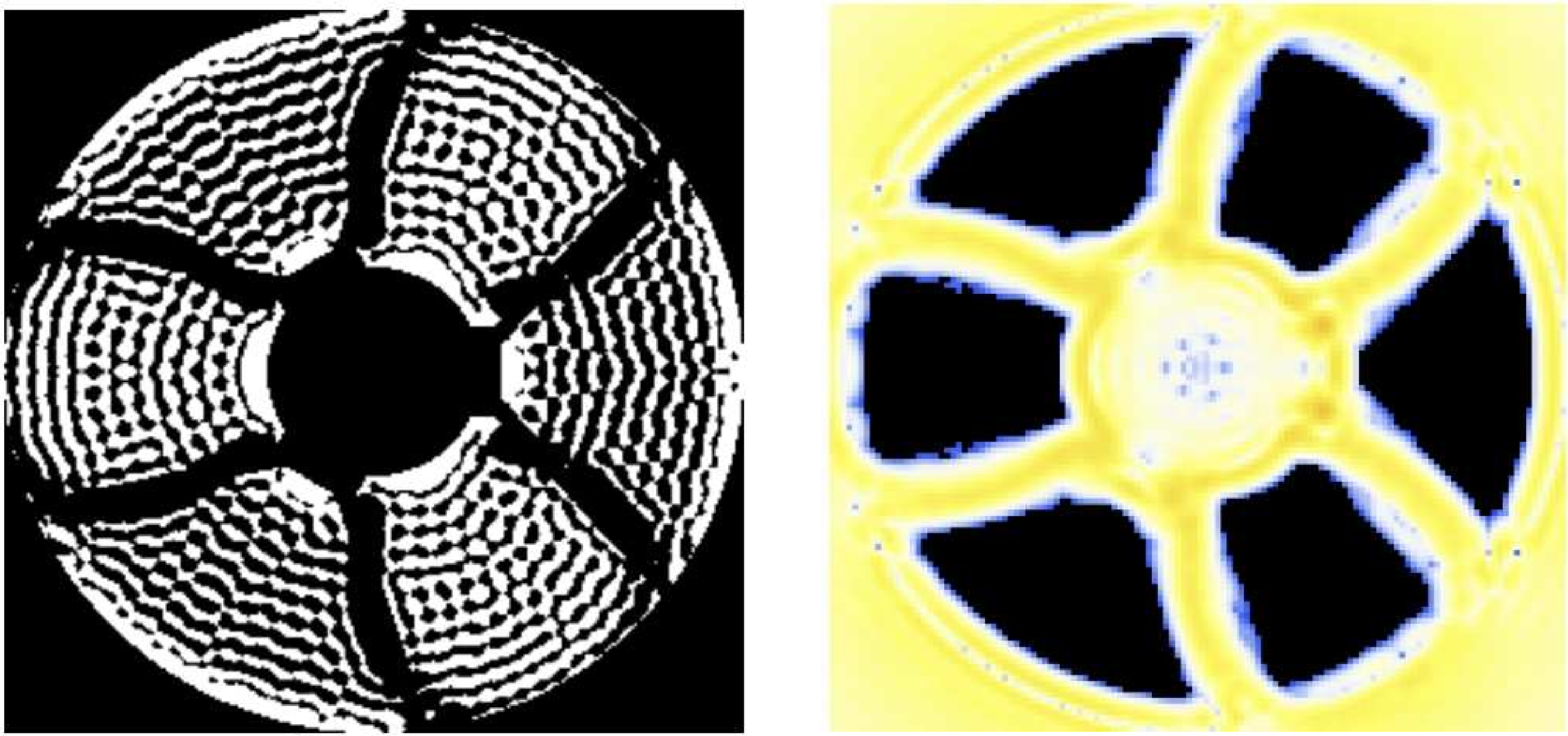






Other high efficiency concepts for AFTA exist

Ongoing Vortex coronagraph work to support AFTA pupil (Mawet, Carlotti)



Carlotti, 2013

Comparative study of coronagraph systems for direct imaging of Earth analogs (1 Earth radius, Earth albedo, 1 AU equivalent distance)

	Baseline 2.4	PIAACMC 2.4	TPF FB1	Notes
Telescope diameter	2.4 m		8 x 3.5 m	
Efficiency	20%			coatings, detector
Wavelength	0.5 um			
Spectral bandwidth	0.1 um (R=5)			
Zodi background	m_V=22 arcsec^{-2}			
Exozodi	2x zodi			
IWA	3 l/D	1.0 l/D	4 l/D	PIAACMC IWA increased to 1l/D due to stellar angular size
Throughput	20%	100%	30%	
Airy efficiency	50%	100%	50%	affects sensitivity due to background (zodi+exozodi)
PSF size	2 l/D	1 l/D	3 l/D (2x4.6 l/D)	
Discovery space	100%	100%	100%	

Assuming detection limit is set by both calibration limit and photon noise:

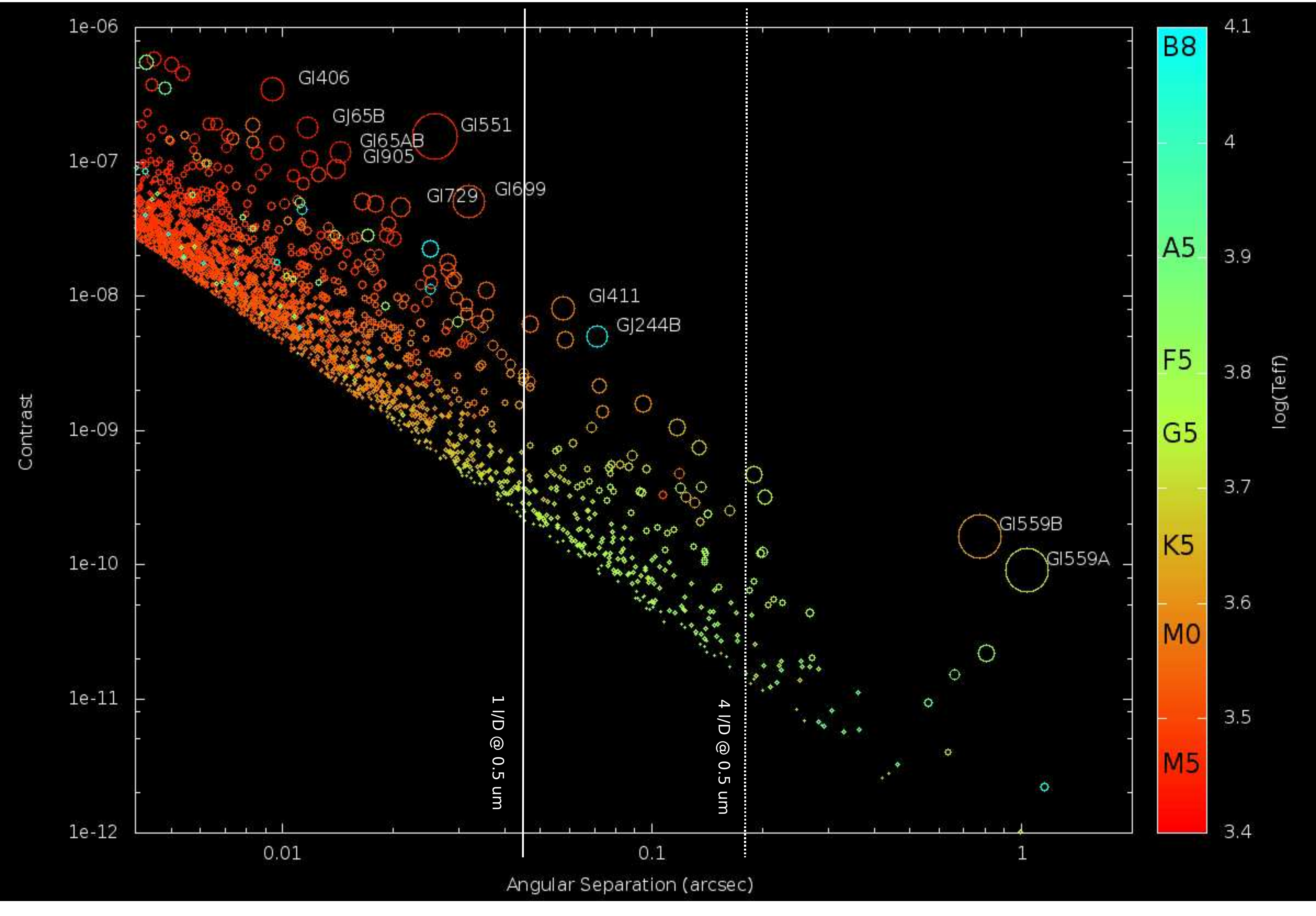
If planet is 1000x fainter than raw contrast, or if inside IWA, SNR = 0

otherwise, SNR driven by photon noise (zodi + exozodi + instrument contrast + planet)

Contrast = 1.74e-10 for Earth analog around Sun

Using catalog produced by merging Hipparcos, SUPERBLINK, Gliese, RECONS and 2MASS
→ 2581 stars within 20pc (most of them M type)

Earth analogs (1 Earth radius, Earth albedo, 1-AU equivalent distance)



Earth analogs (1 Earth radius, Earth albedo, 1-AU equivalent distance)

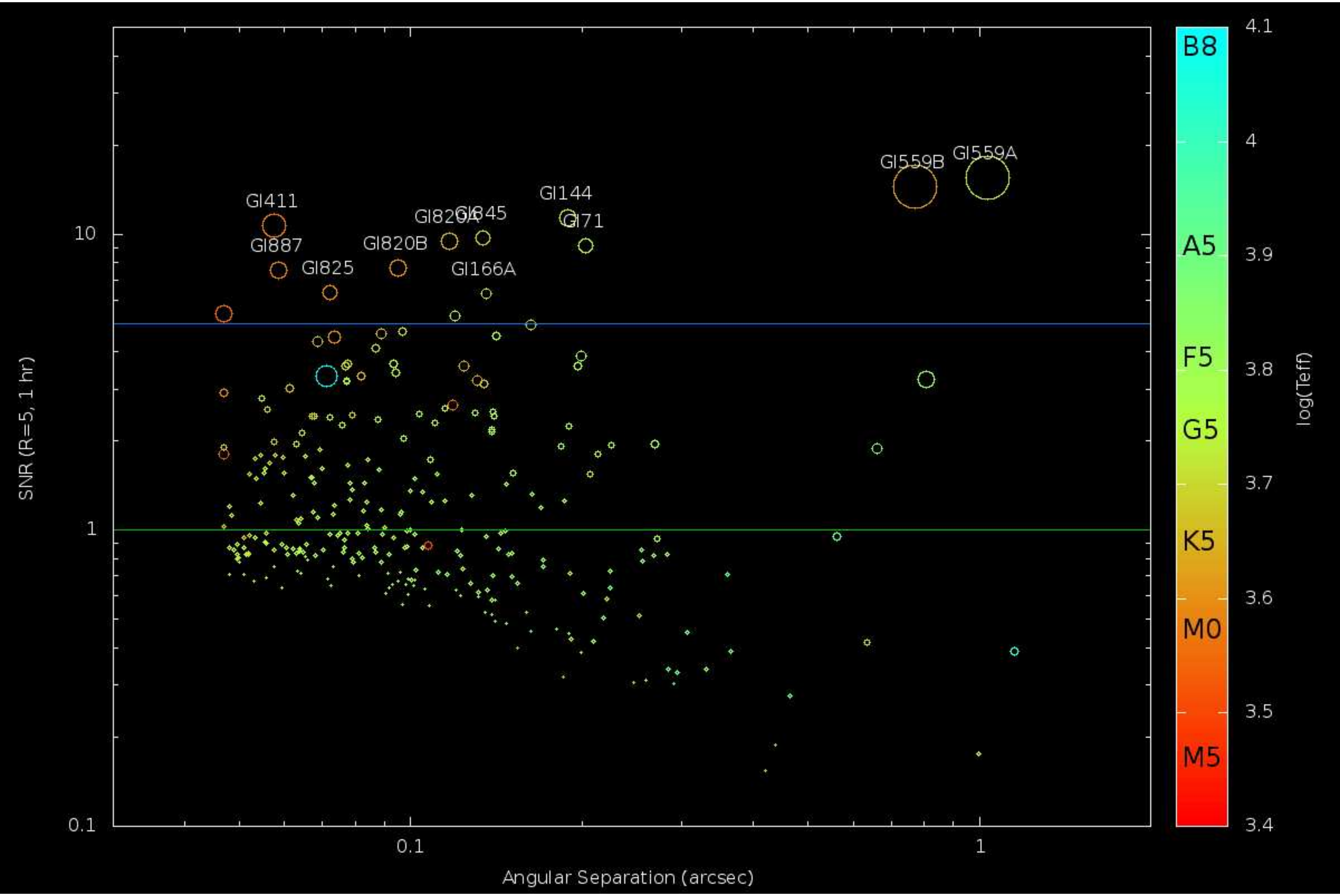
The next slides show SNR for 1hr observation at R=5 for various coronagraph configurations and raw contrast level

The size of each circle is inverse proportional to system distance. The color shows the star spectral type.

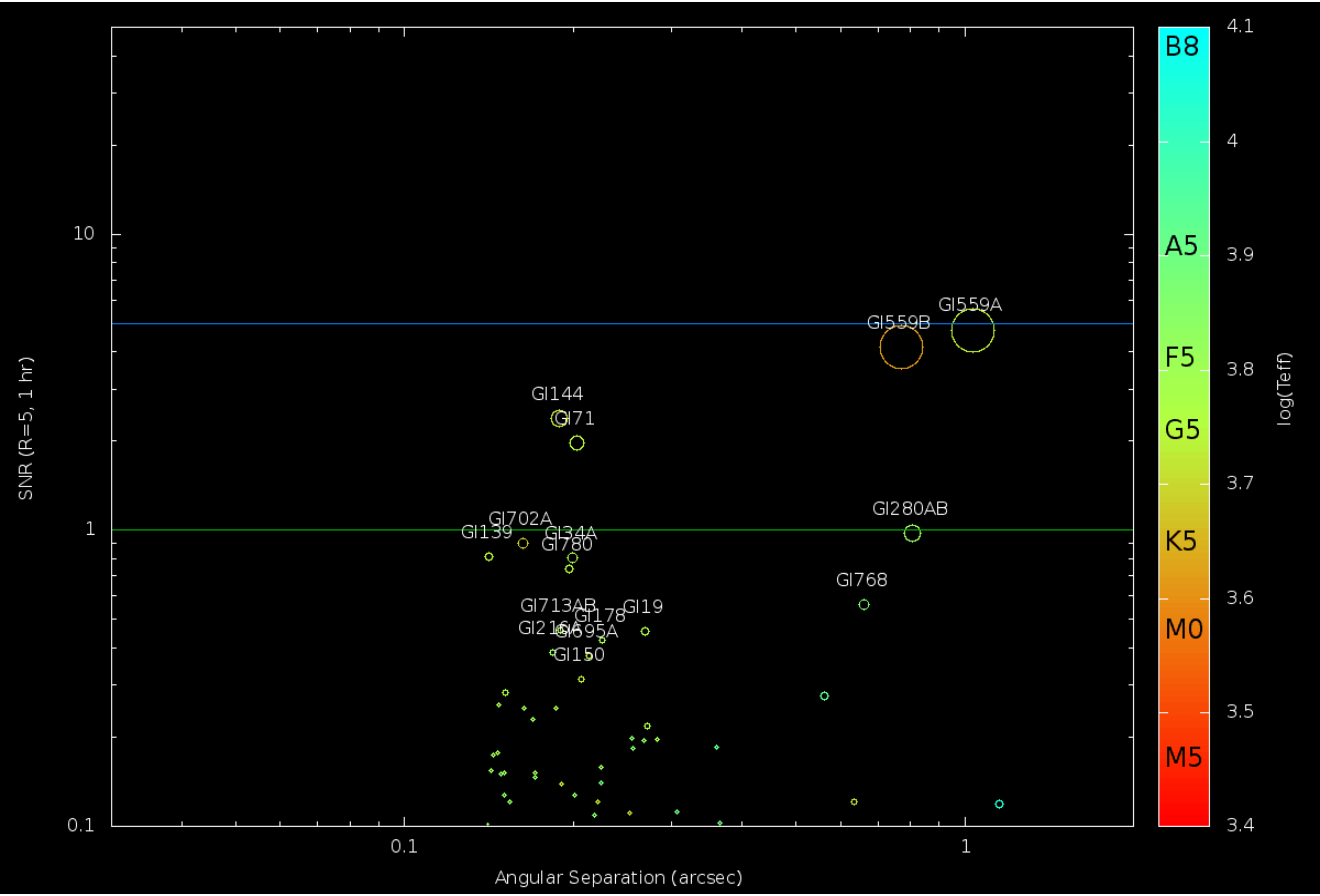
Targets above the horizontal green line (SNR = 1) can be detected and their colors identified with 1 day observation.
SNR=1, R=5 in 1hr corresponds to SNR=5 @ R=5 in 1 day.

Targets above the horizontal blue line (SNR = 5) can be characterized in 1 day.
SNR=5, R=5 in 1hr corresponds to SNR=5 @ R=120 in 1 day.

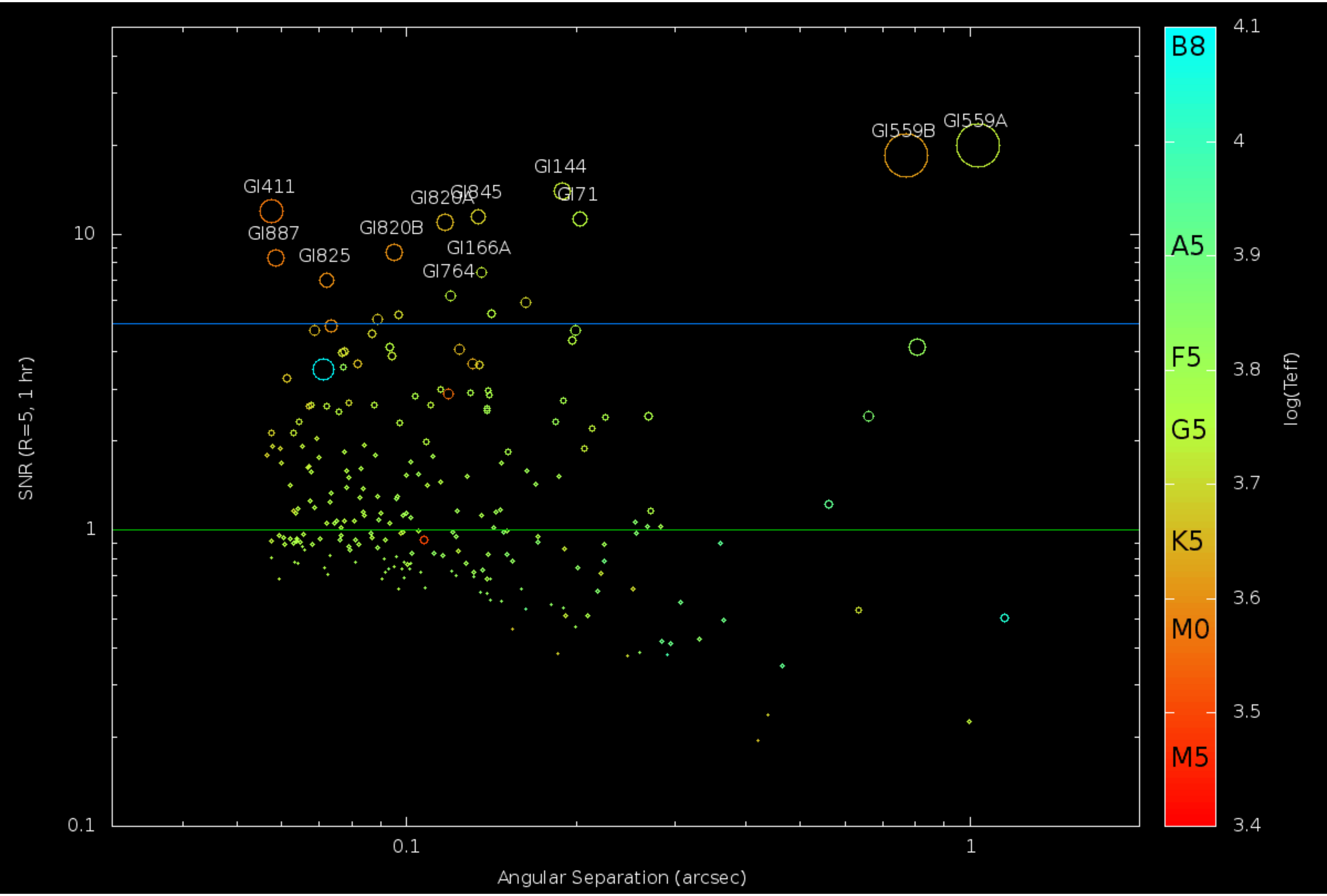
PIAACMC, 1e-9 RAW instrument contrast



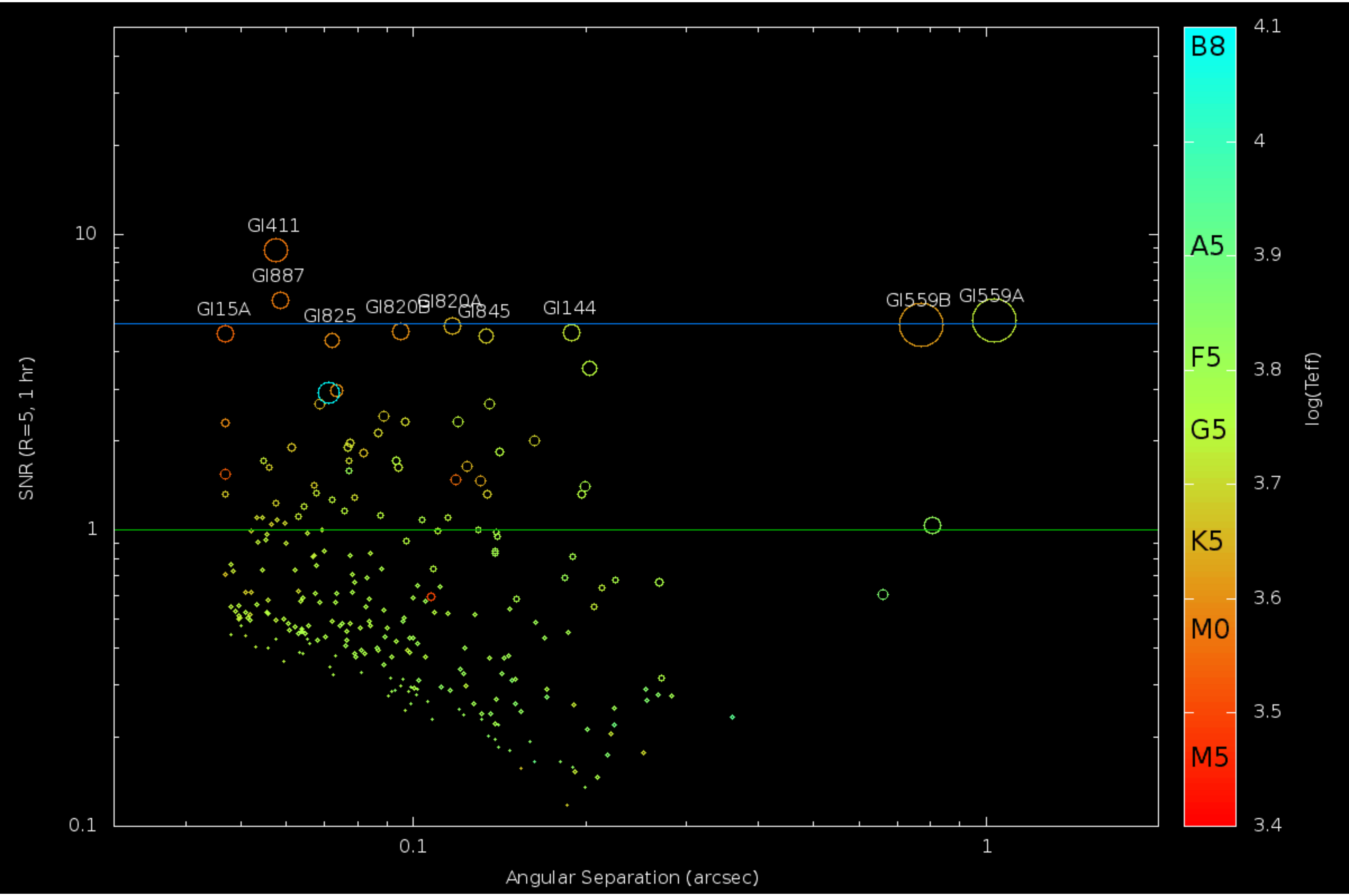
Baseline, 1e-9 RAW instrument contrast



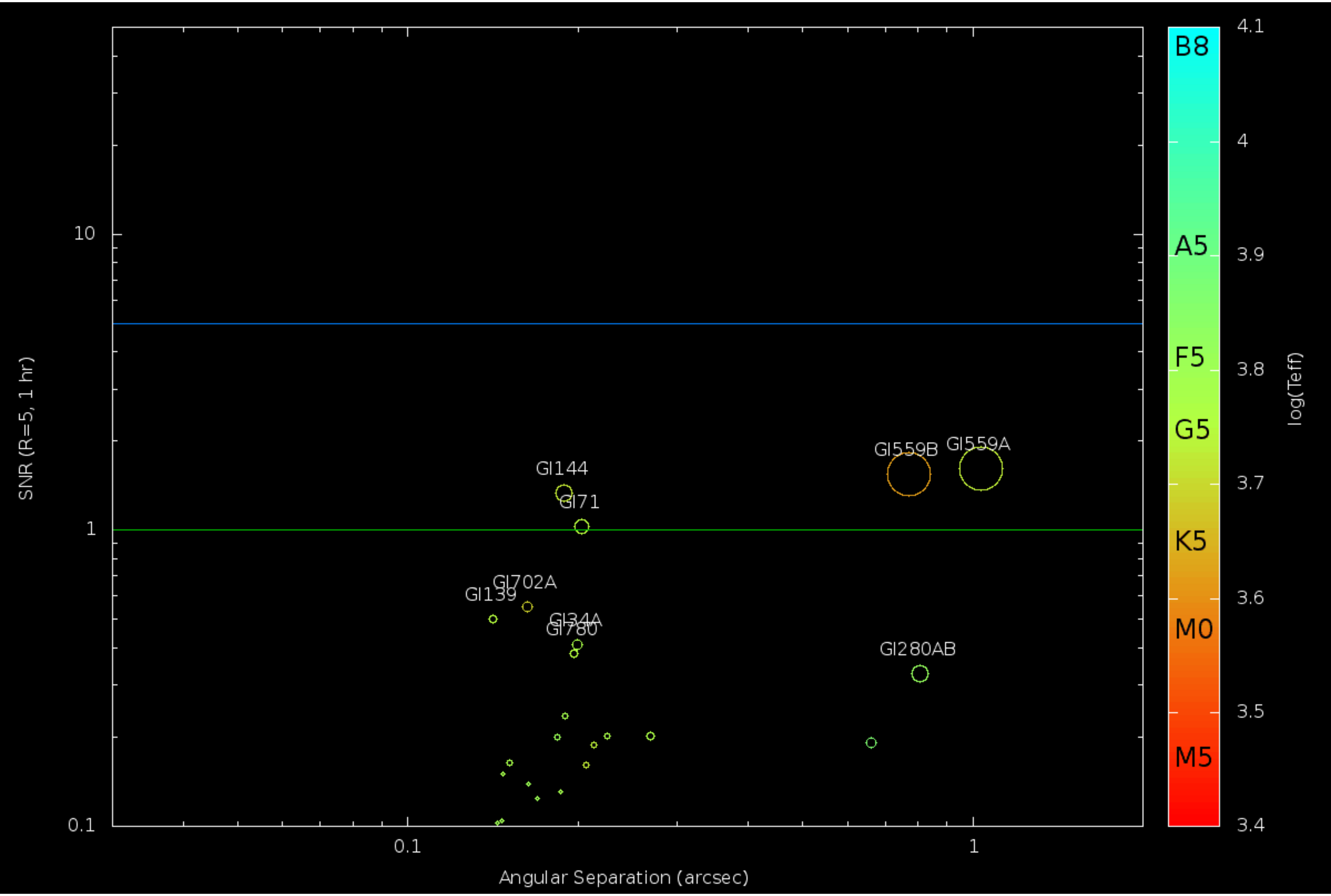
TPF-C FB1, 1e-9 RAW instrument contrast



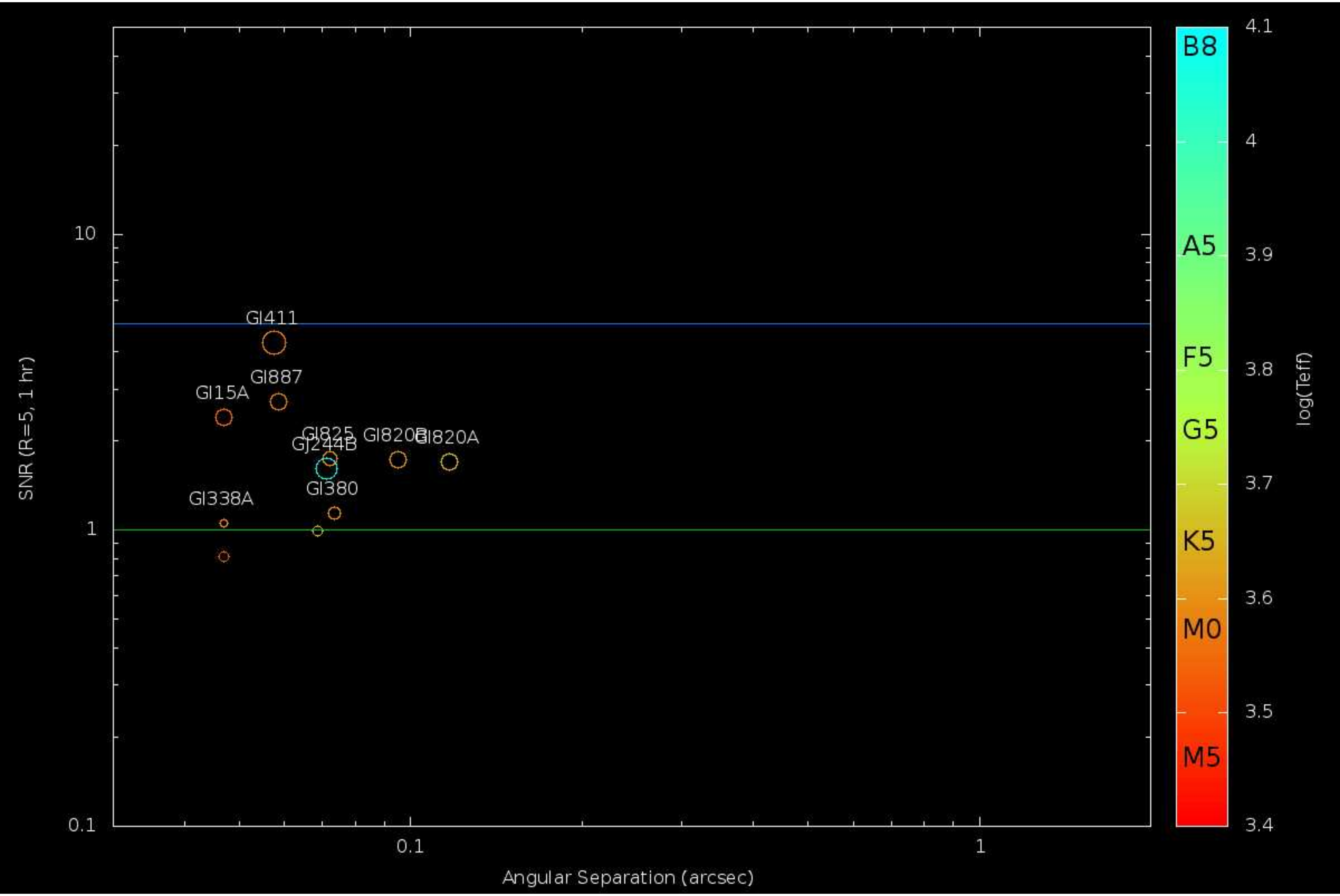
PIAACMC, 1e-8 RAW instrument contrast



Baseline, 1e-8 RAW instrument contrast



PIAACMC, 1e-7 RAW instrument contrast, 1% calibration limit



Important findings

With full efficiency coronagraph, 2.4-m telescope could potentially detect and characterize habitable Earth-like planets around ~10 to 20 stars

requires instrument contrast ~1e-7 at 1-3 l/D, and ~1e-8 at 3-30 l/D

requires calibration to ~1e-8 contrast at 1-3 l/D, and to ~1e-9 / 1e-10 at 3-30 l/D

Performance gain comes both from lower IWA (access to more planets, brighter and at more moderate contrast) and higher efficiency

For planets that are outside the IWA of both baseline and PIAACMC, the PIAACMC is 50x more efficient (same SNR with 50x less exposure time) than baseline

The PIAACMC, even if working at only 1e-7 raw contrast would detect more Earth-like planets (around 9 stars) than the baseline coronagraph would if working at 1e-9 contrast (around 3 stars). Note that the stars sampled are different (no overlap in target list).

PIAACMC on 2.4m telescope: scientific return is potentially comparable to TPFC-FB1, on a sample ~1/2 the size

Important findings

BUT, more work/study is needed:

Accurately take into account stellar angular size for each target
Establish requirements for telescope stability
Design work and lab testing for PIAACMC, with special attention to chromaticity
Model exozodi & its impact

What will tell us if a high efficiency coronagraph option is feasible ?

(1) Lab raw contrast demonstration needs to reach at least ~1e-7 at 1-3 l/D, and ~1e-8 at 3-30 l/D in polychromatic light

(2) Need to demonstrate that telescope stability is sufficiently good to reach and maintain this contrast

(3) Need to understand and demonstrate detection contrast

Coronagraph choice and contrast
(we need to become quantitative...)

Low IWA coronagraph comes with high sensitivity to low order aberrations.
In a passive system, it is considerably harder to maintain high contrast at small IWA than at large angular separation.

However:

Small IWA coronagraph does not require as good a contrast as a large IWA system.
Raw contrast can be relaxed by >100x by adopting a high efficiency coronagraph (compare slides 15 and 19)
PIAACMC can do R~100 spectroscopy of Earth analogs around a few stars in 1 day with a 1e-8 raw instrumental contrast (slide 17)

In an active system, efficient coronagraph means efficient wavefront sensing and control → telescope stability can be relaxed
mid and high spatial frequencies: PIAACMC is 50x more efficient than baseline for detecting faint sources (background-limited regime), and 10x more efficient than baseline for bright sources → at the same contrast level, telescope wavefront drift can be 10x to 50x faster if a high efficiency coronagraph is used.
low order aberrations can be sensed efficiently using all starlight with a low-order WFS